Phenomenological approach to two-photon detection

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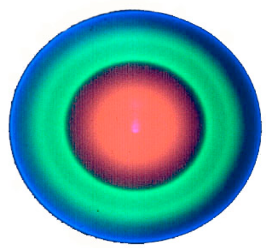


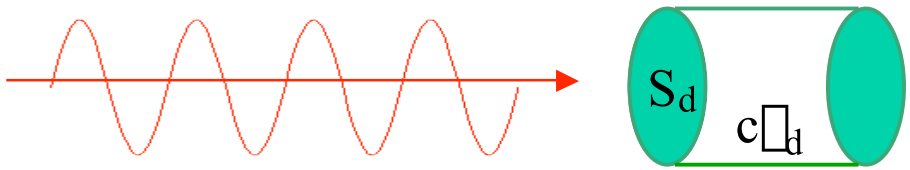
Phenomenological approach allows one to compare detection efficiencies for classical and quantum-correlated light fields.

Outline

- Why two-photon detection: quantum cryptography, quantum lithography, quantum logic, quantum metrology and interferometry
- A simple detection model for a “Bucket detector”
- Application to two-photon absorption in media: “Virtual detectors”
- Two-photon lithography experiment
- Application to coherent up-conversion: “6D detector”
- Two-photon up-conversion experiment
- Transverse correlation of a biphoton
- Photoelectric effect in a biphoton field
- Summary

Two-photon "bucket" detector in a coherent field

Coherence (mode) volume V_c Detection volume V_d



$$p(n) = \frac{\left(<n> \frac{V_d}{V_c}\right)^n}{n!} e^{-<n>\frac{V_d}{V_c}}$$

$$p(n) = \frac{<n>^n}{n!} e^{-<n>}$$

Probability to get exactly one: $p_1 = <n> \frac{V_d}{V_c} e^{-<n>\frac{V_d}{V_c}}$

Probability to get exactly two: $p_2 = \frac{1}{2}\left(<n> \frac{V_d}{V_c}\right)^2 e^{-<n>\frac{V_d}{V_c}}$

$\ldots$

$\frac{V_d}{V_c} > 1$ multi-mode detector $\frac{V_d}{V_c} < 1$ sub-mode detector

"To get" does not always mean "to detect". Any pair can be detected with probability $\eta^{(2)}$ so the probability to detect 2 out of *n* is

$$p_{2|n} = \eta^{(2)} C_n^2$$

$$\boxed{\frac{<n>}{V_c} = \frac{I}{c\hbar\omega},}$$

And the mean number of pair detections (for small $\eta^{(2)}$) is

$$P_{cl}^{(2)} = \eta^{(2)} e^{-<n>\frac{V_d}{V_c}} \sum_{k=2}^{\infty} \frac{\left(<n> \frac{V_d}{V_c}\right)^k}{k!} C_k^2 = \frac{\eta^{(2)}}{2}\left(<n> \frac{V_d}{V_c}\right)^2 = \boxed{\frac{\eta^{(2)}}{2}\left(\frac{I V_d}{c\hbar\omega}\right)^2}$$

Two-photon "bucket" detector in a biphoton field

If V_{corr} is smaller than V_d ,

$$P_q^{(2)} = \eta^{(2)} \frac{<n>}{2} \frac{V_d}{V_c} e^{-\frac{<n>}{2}\frac{V_d}{V_c}}$$

$$= \frac{\eta^{(2)}}{2} \frac{IV_d}{c\hbar\omega} e^{-\frac{IV_d}{2c\hbar\omega}}$$

Ratio of detection rates for biphoton and coherent fields of the same intensity:

$$\frac{P_{bph}^{(2)}}{P_{coh}^{(2)}} \approx \frac{c\hbar\omega}{IV_d} e^{-\frac{IV_d}{2c\hbar\omega}}$$

For weak fields:

$$\frac{P_{bph}^{(2)}}{P_{coh}^{(2)}} \approx \frac{c\hbar\omega}{IV_d}$$

Which is consistent with the earlier result

[D.N. Klyshko, Sov. Phys. JETP ***56****, 753 (1982)]*

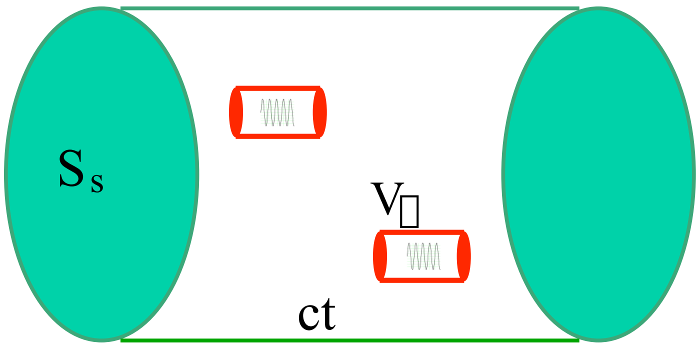
$$\frac{P_{bph}^{(2)}}{P_{coh}^{(2)}} \approx \frac{\mathrm{M}}{<n>}$$

where

$$\mathrm{M} = \frac{V_d}{V_c}$$

is the number of detected modes.

Two-photon absorption in bulk media: “virtual detectors”



Distribution of singles (“virtual detectors”) in the sample volume V_d = ct S_s is

$$p(n) = \frac{\left(< n > \frac{V_d}{V_c}\right)^n}{n!} e^{-<n>\frac{V_d}{V_c}}$$

For each “virtual detector”, in the case of Poissonian statistics :

$$p'(n) = \frac{1}{n!}\left(< n > \eta^{(2)}\frac{V_\sigma}{V_c}\right)^n e^{-<n>\eta^{(2)}\frac{V_\sigma}{V_c}}$$

So the probability that is will fire is:

$$P_f = 1 - p'(0) \approx < n > \eta^{(2)}\frac{V_\sigma}{V_c}$$

and the mean-number of absorbed photon pairs will be:

$$N(t) = \sum_{n=0}^{\infty} n\, p(n)\, P_f = < n >^2 \eta^{(2)}\frac{V_\sigma V_s}{V_c^2}\frac{t}{\tau_c}$$

$$= \left(\frac{I}{c\hbar\omega}\right)^2 \eta^{(2)} V_\sigma V_s \frac{t}{\tau_c}$$

As expected, the two-photon signal from uncorrelated light is quadratic in intensity and linear with respect to the exposure time.

In the case of photon pairs that are correlated within the volume V_{corr} ,

$$P_f = \eta^{(2)} \begin{cases} 1 & V_{corr} < V_{\square} \quad \text{“if there is one, there is always the other”} \\ \dfrac{V_\sigma}{V_{corr}} & V_{corr} > V_{\square} \quad \text{“if there is one, there may be the other”} \end{cases}$$

Then the mean-number of absorbed photon pairs is

$$N(t) = \frac{I}{c\hbar\omega}\frac{t}{\tau_c}\eta^{(2)}V_s \begin{cases} 1 & V_{corr} < V_{\square} \\ \dfrac{V_\sigma}{V_{corr}} & V_{corr} > V_{\square} \end{cases}$$

Comparing with the result for uncorrelated light, we get for equal exposure times

$$\frac{N_{corr}}{N_{coh}} = \frac{I_{corr}}{I_{coh}}\frac{\tau_c^{coh}}{\tau_c^{corr}}\frac{c\hbar\omega}{I_{coh}}\min\left\{\frac{1}{V_\sigma}, \frac{1}{V_{corr}}\right\}$$

We can also compare a SW exposure of duration ***t*** with correlated light to a pulse exposure with coherent light. In this case we get

$$\frac{N_{corr}}{N_{coh}} = \frac{I_{corr}}{I_{coh}} \frac{t}{\tau_c^{corr}} \frac{c\hbar\omega}{I_{coh}} \min\left\{\frac{1}{V_\sigma}, \frac{1}{V_{corr}}\right\}$$

For order-of-magnitude estimate $\min\left\{\frac{1}{V_\sigma}, \frac{1}{V_{corr}}\right\} \approx \left(\lambda^2 \tau_0 c\right)^{-1}$

$\boxed{\lambda = 700\ \text{nm},\ \tau_0 = 100\ \text{fs},\ \Delta\lambda = 100\ \text{nm},\ I_{corr} = 5\ \text{W/m}^2}$

$I_{coh} \sim 1\ \text{GW/cm}^2$

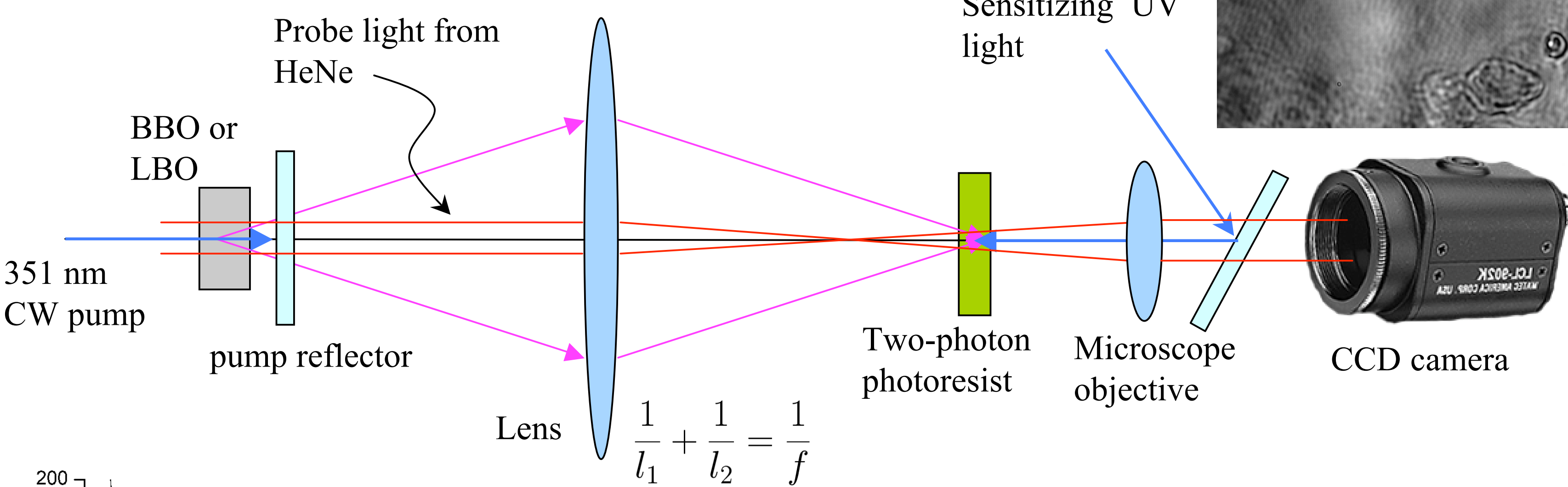
$$\frac{N_{corr}}{N_{coh}} \approx 0.3\ t\ [\text{s}]$$

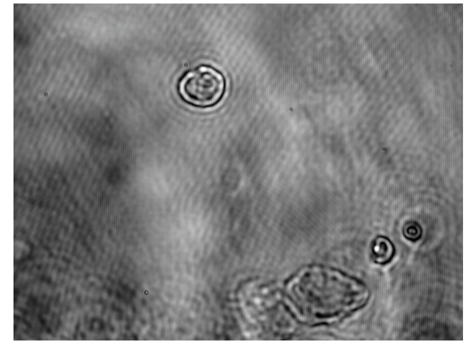
It should be possible to get exposure in 3 seconds!

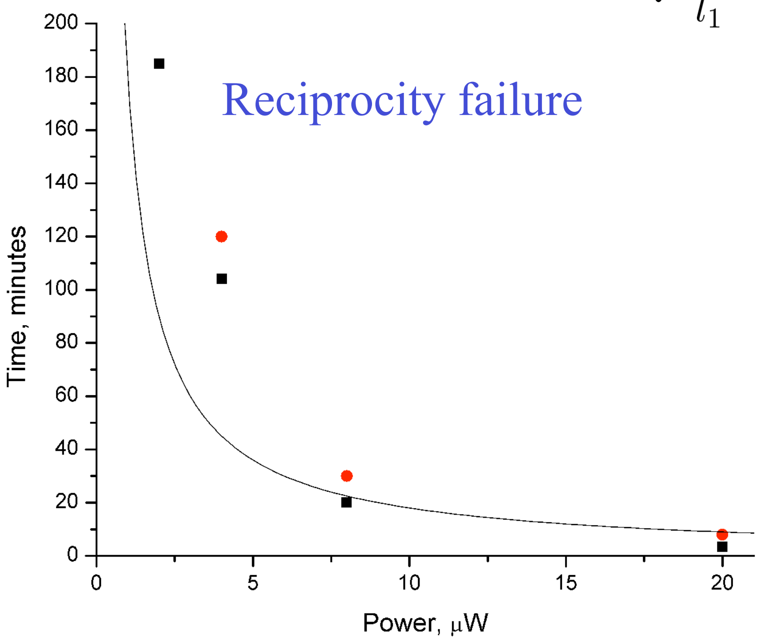
*[R.A. Borisov et al., Appl. Phys. B **67**, 765 (1998)]*

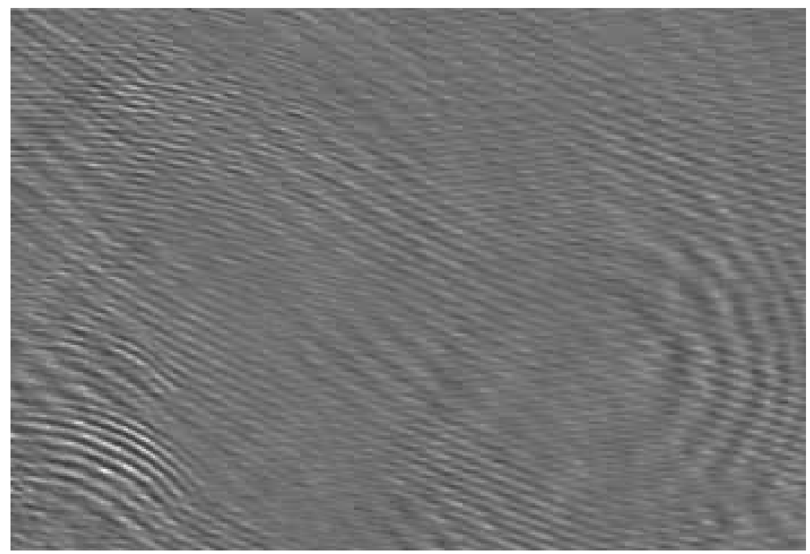
*[Y. Boiko et al., Opt. Express **8**, 571 (2001)]*

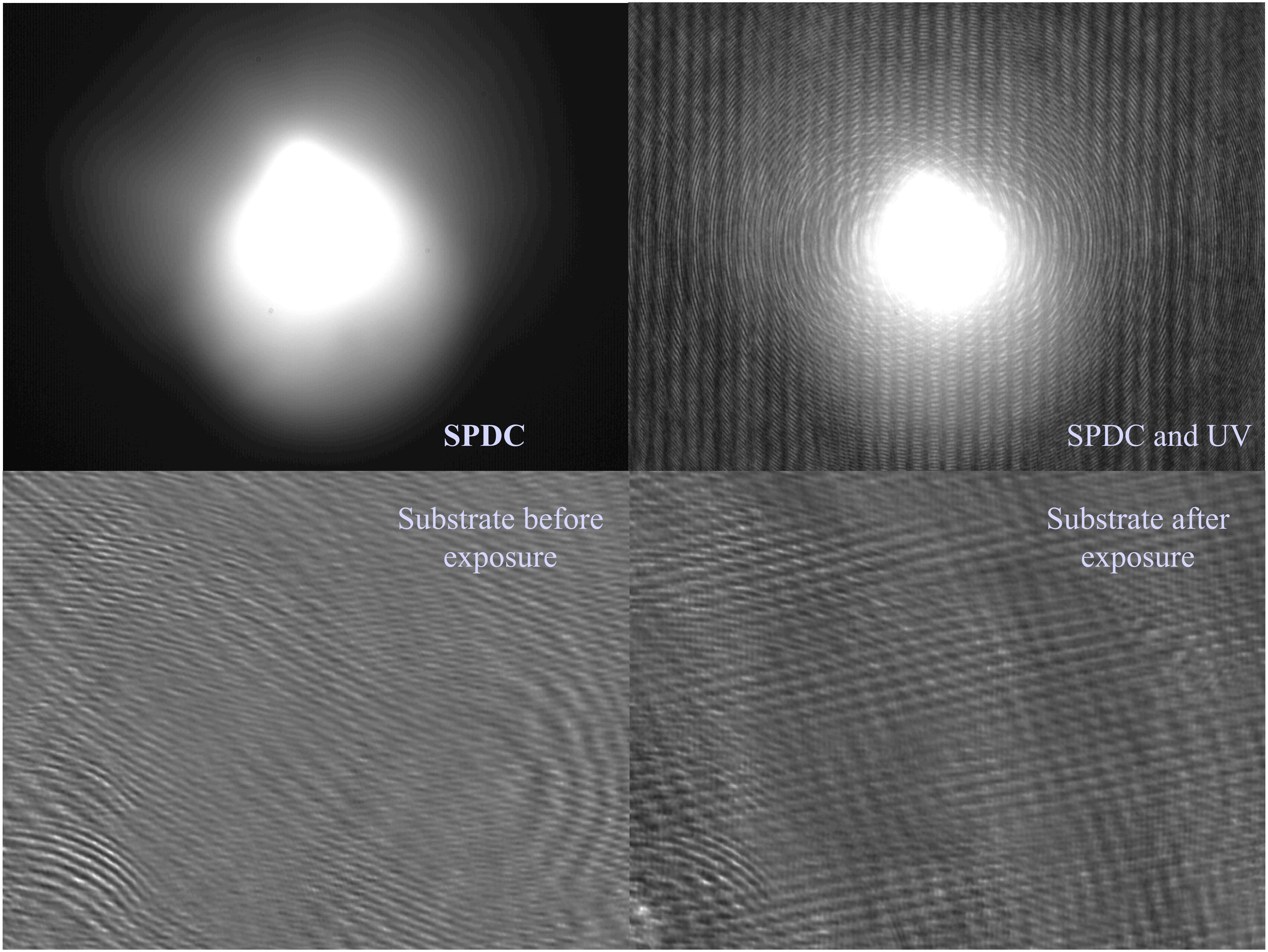
Two-photon lithography experiment



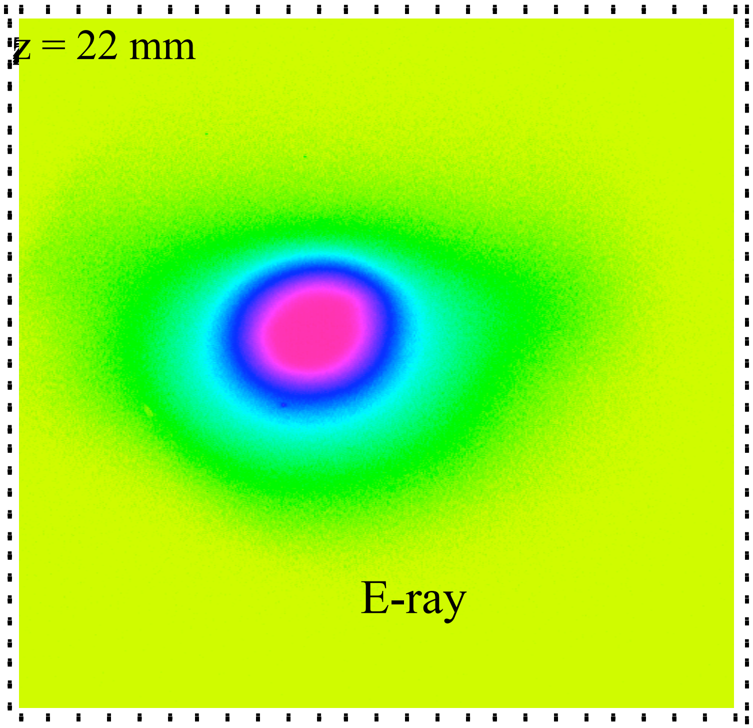


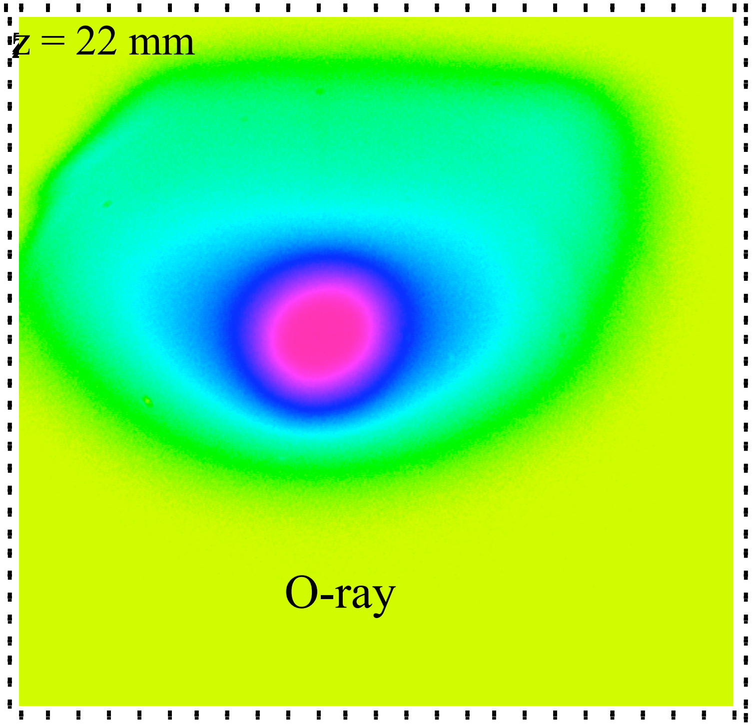





SPDC
SPDC and UV
Substrate before exposure
Substrate after exposure

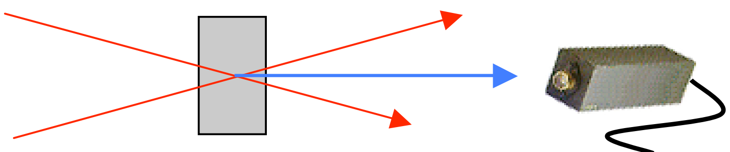
Focusing SPDC light





Detection by coherent up-conversion

$$\omega_s + \omega_i = \omega_p,$$
$$\vec{k}_s + \vec{k}_i = \vec{k}_p,$$



Up-converting crystal

Photon counter

Number of detected modes $M = \dfrac{V_d}{V_c}$ - ??

$$\boxed{V = \Delta k_x \Delta k_y \Delta k_z \Delta x \Delta y \Delta z}$$

For a single mode, $V = (2\square)^3$

For coherent light, $R_{coh} = \eta^{(2)} \underbrace{M_c < n >}_{\text{number of “first” photons}} < n >$

□ □(2)

number of “second” photons

For two-photon (SPDC) light, $R_{spdc} = \eta^{(2)} M_{spdc} < n >$

$$\xi \equiv \frac{R_{spdc}}{R_{coh}} = \frac{M_{spdc} < n >_{spdc}}{M_{coh} < n >^2_{coh}}$$

The number of modes M is $$M = \frac{V}{(2\pi)^3} = \frac{AL}{(2\pi)^3}\frac{k^2}{c}\Delta\Omega\Delta\omega$$

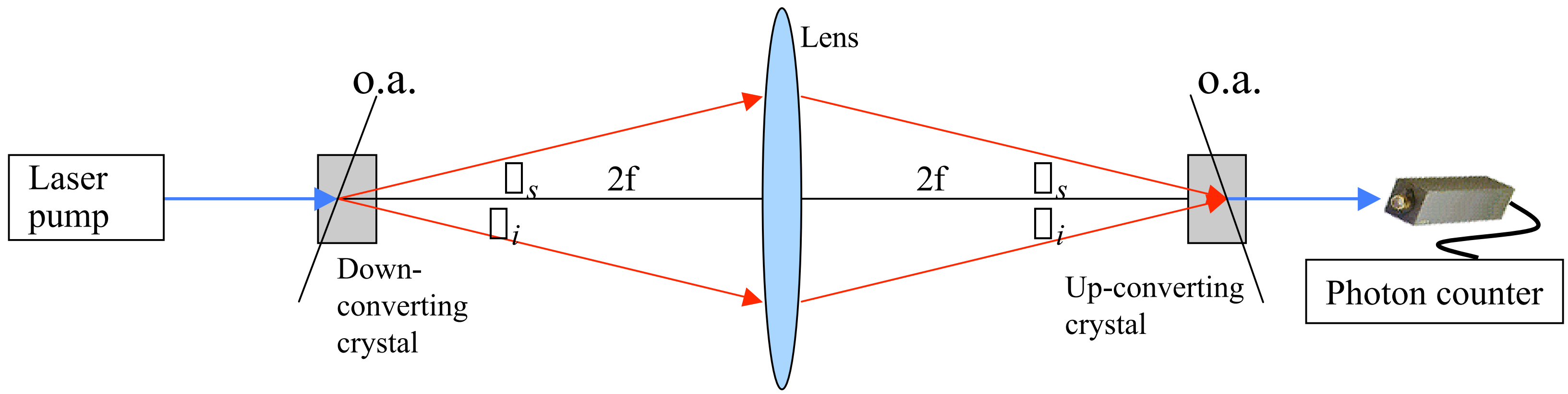
Comparing for equal intensities: $$\xi = \frac{\hbar c \Delta\Omega_{coh}\Delta\omega_{coh}}{I\lambda^3}.$$

Estimates:

$I \approx 5\, W/m^2$ $\quad \Delta\omega_{coh} \approx 4 \times 10^{13}\, s^{-1}$ $\quad \Delta\Omega \approx 2\pi\theta_d^2 \approx 3 \times 10^{-4}$ st. radians

$$\boxed{\xi \approx 200}$$

Correlation-enhanced optical up-conversion



For coherent CW pump:

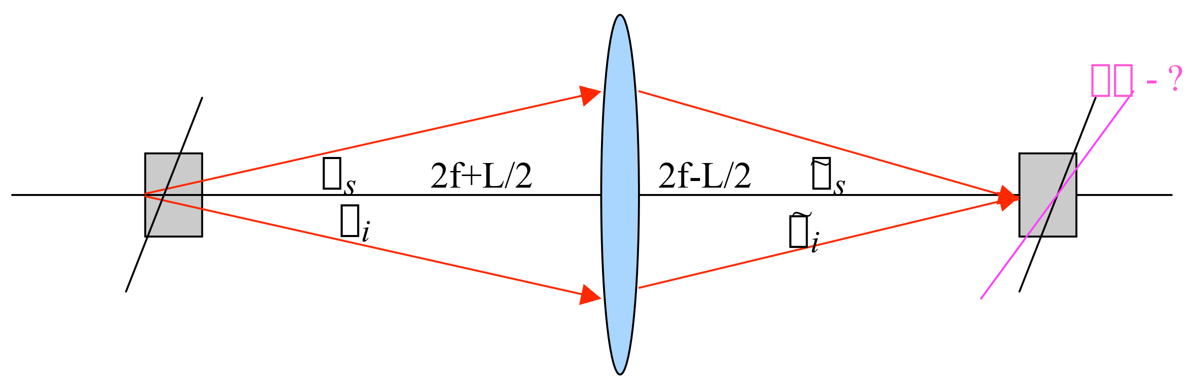
1W pump ⟶ 10^{-5} W of SH

50 nW pump ⟶ $1.5*10^{-20}$ W

or about 0.3 photons/s of SH

With the biphoton enhancement factor 200 and we can expect about 40 photons/s signal.

In a real experiment, the signal may be lower because of alignment and focusing angular errors and the effects of an extended source.

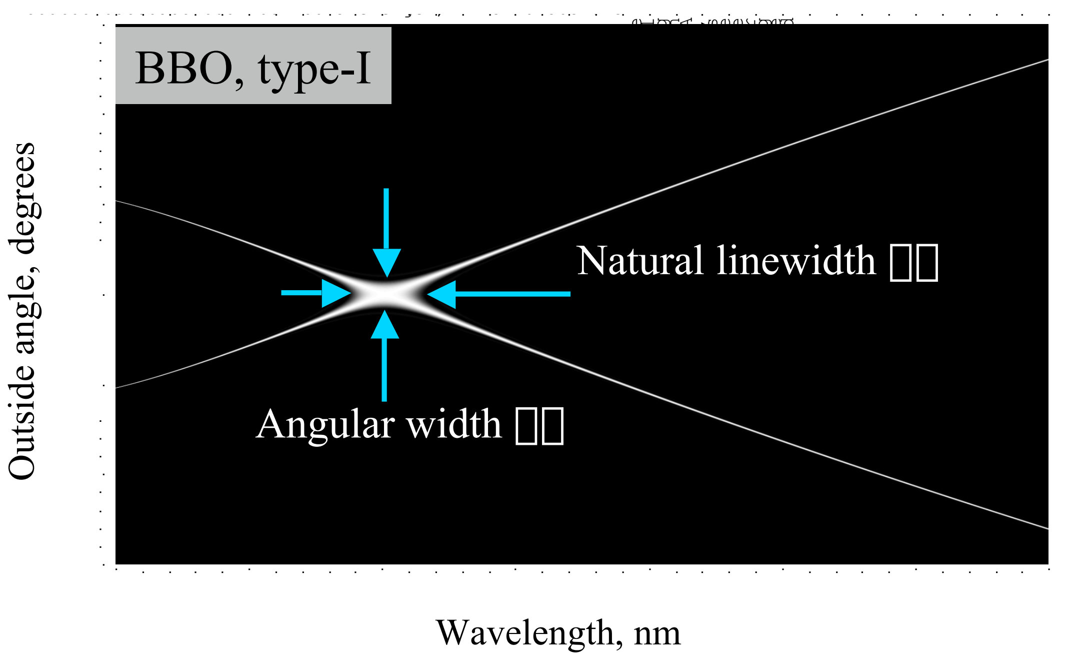


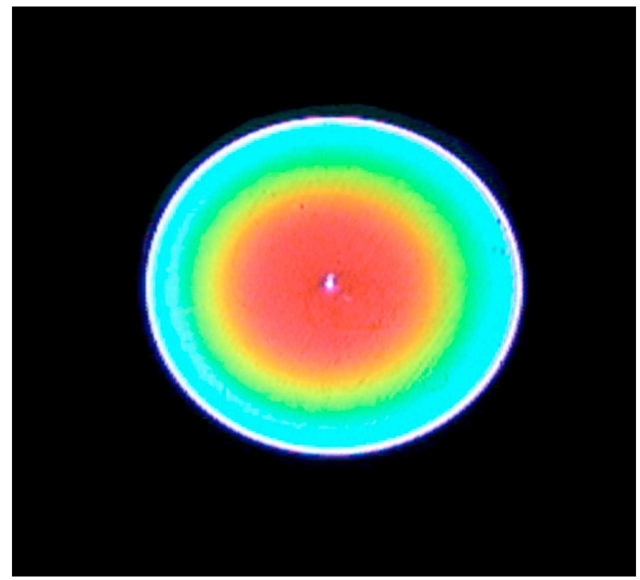
Transverse correlation of a biphoton

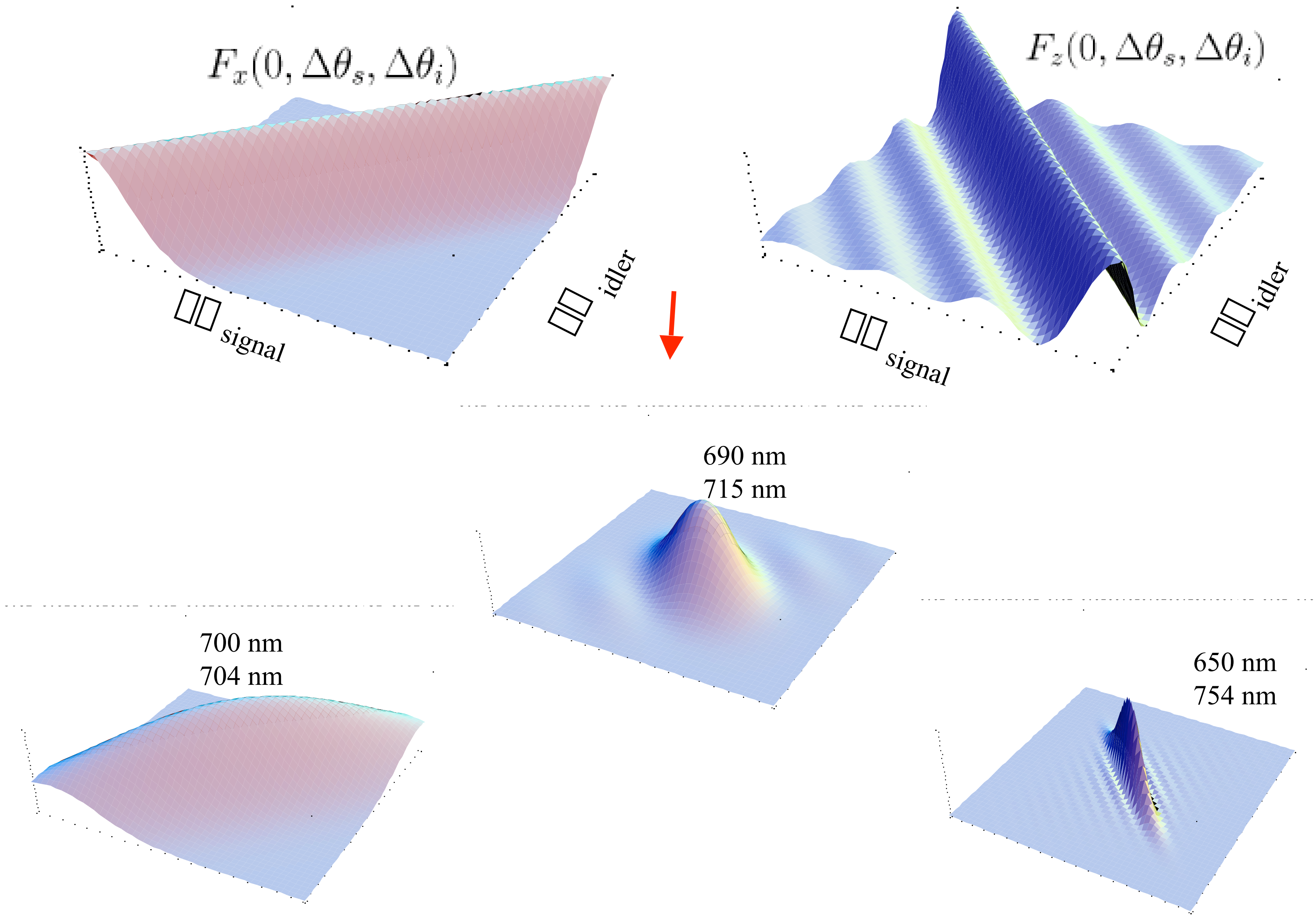
[M.H. Rubin, Phys. Rev. A. ***54****, 5349 (1996)]*
[A.V. Burlakov et. al, Phys. Rev. A. ***56****, 3214 (1997)]*

$$|\Psi\rangle = \int F(\vec{k}_s, \vec{k}_i)|1\rangle_{\vec{k}_s}|1\rangle_{\vec{k}_i}\, d\vec{k}_s d\vec{k}_i$$

$$F(\vec{k}_s, \vec{k}_i) = F_x(\Delta\omega, \Delta\theta_s, \Delta\theta_i)F_z(\Delta\omega, \Delta\theta_s, \Delta\theta_i)$$

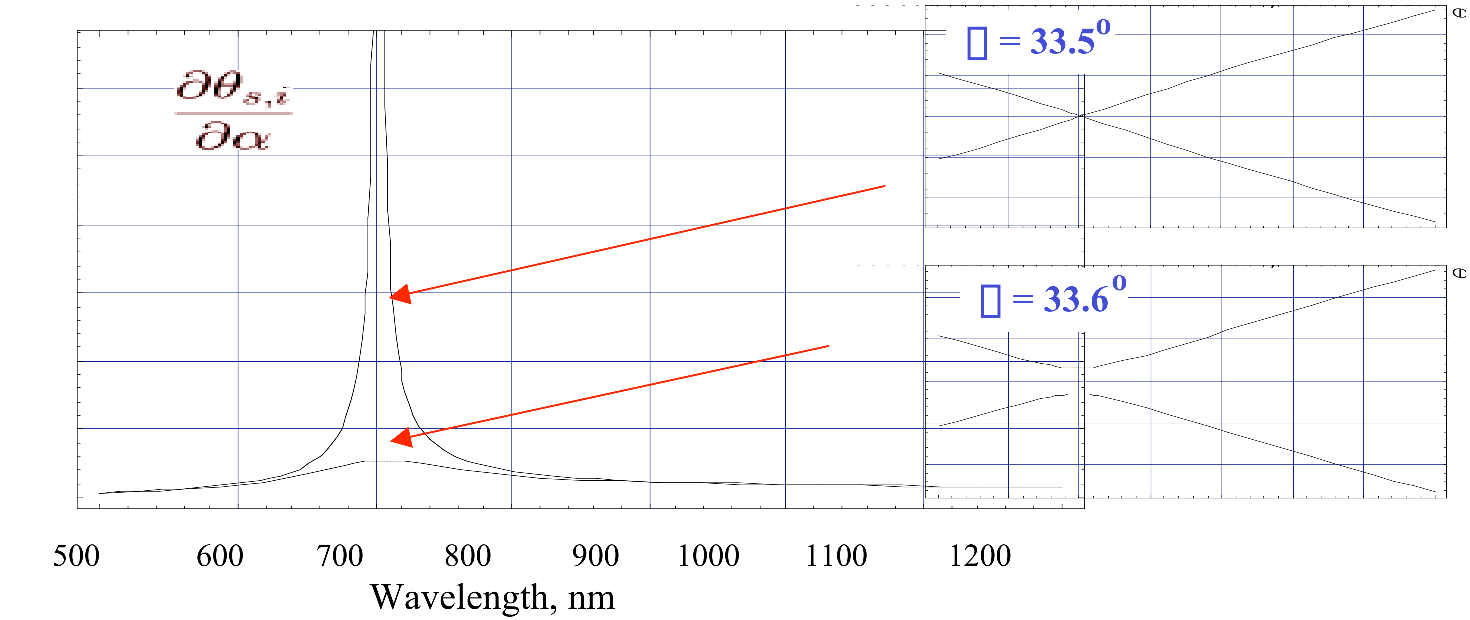




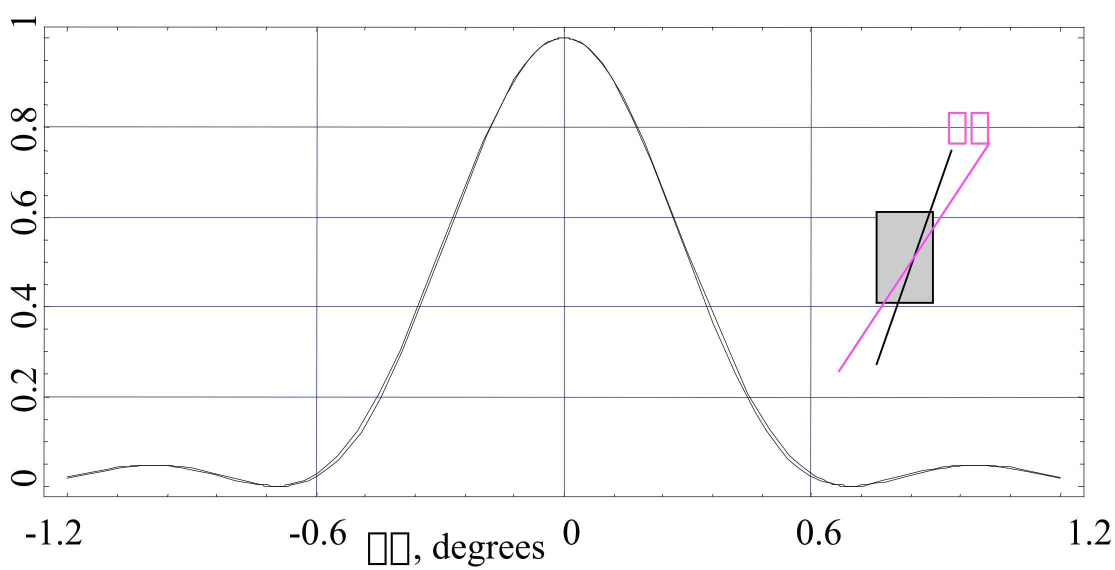


$F_x(0, \Delta\theta_s, \Delta\theta_i)$
signal
idler
$F_z(0, \Delta\theta_s, \Delta\theta_i)$
signal
idler
690 nm
715 nm
700 nm
704 nm
650 nm
754 nm

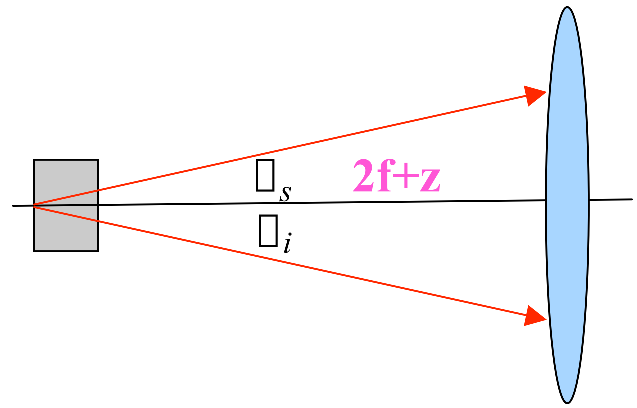
Substituting $\Delta\theta_{s,i} = \frac{\partial\theta_{s,i}}{\partial\alpha}\Delta\alpha$ into F(0, □□$_s$, □□$_i$)



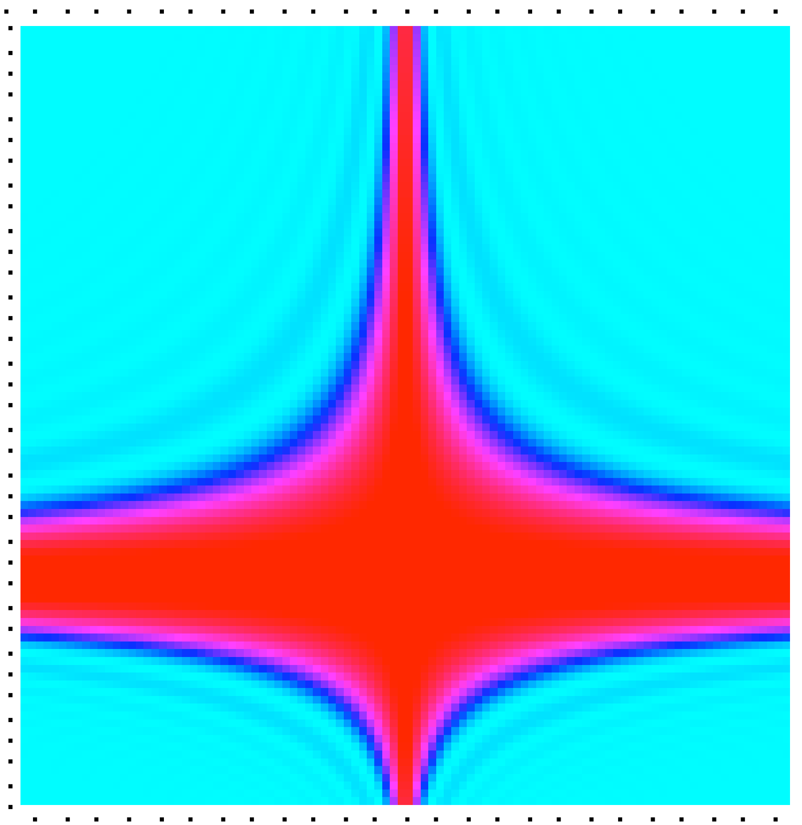
we find the overlap
between the correlation
and detection volumes
as a function
of alignment error:



Substituting □□$_{s,i}$ (z) into F(0, □□$_{s}$, □□$_{i}$)
we get the overlap between the
correlation and detection volumes
as a function of the offset z:

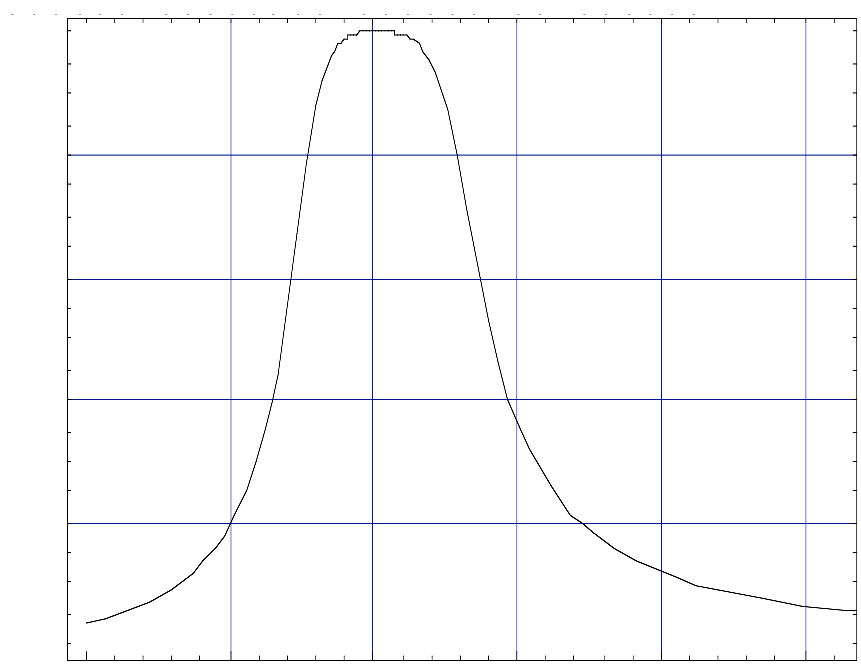


Wavelength, nm



z, mm

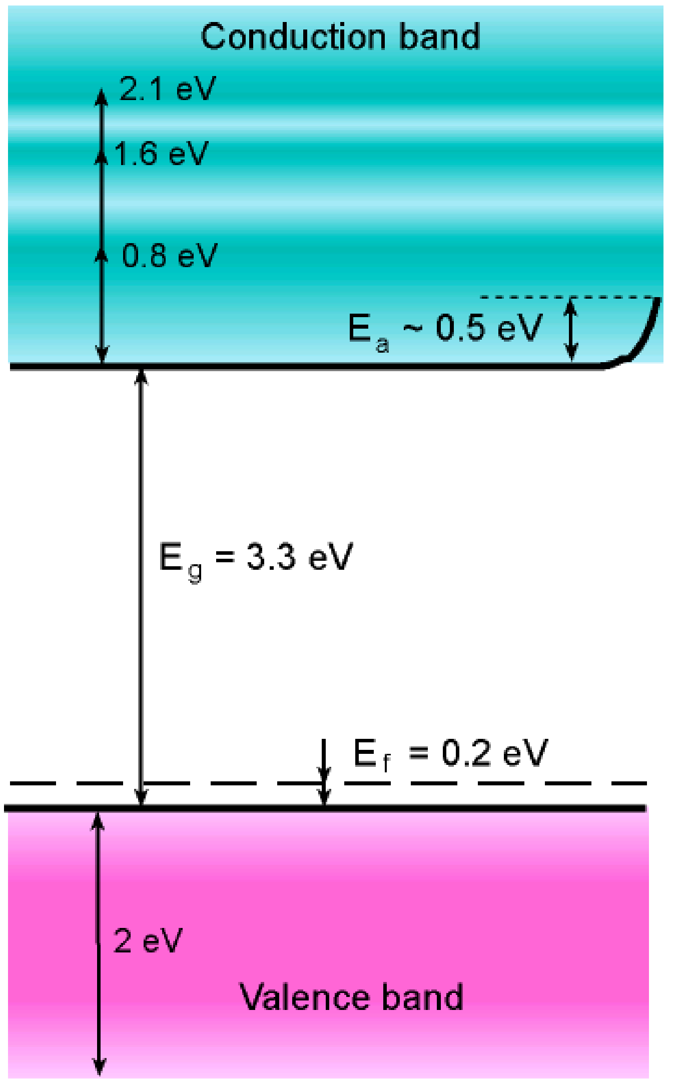
Efficiency for a 5 mm - long crystal:



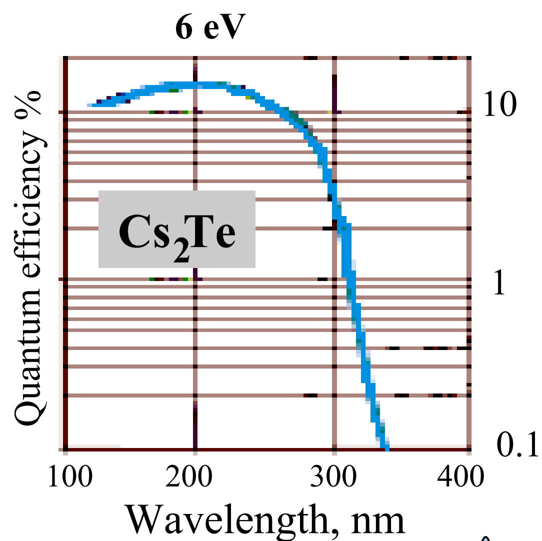
Wavelength, nm

Photoelectric effect in Cs_2Te photocathode

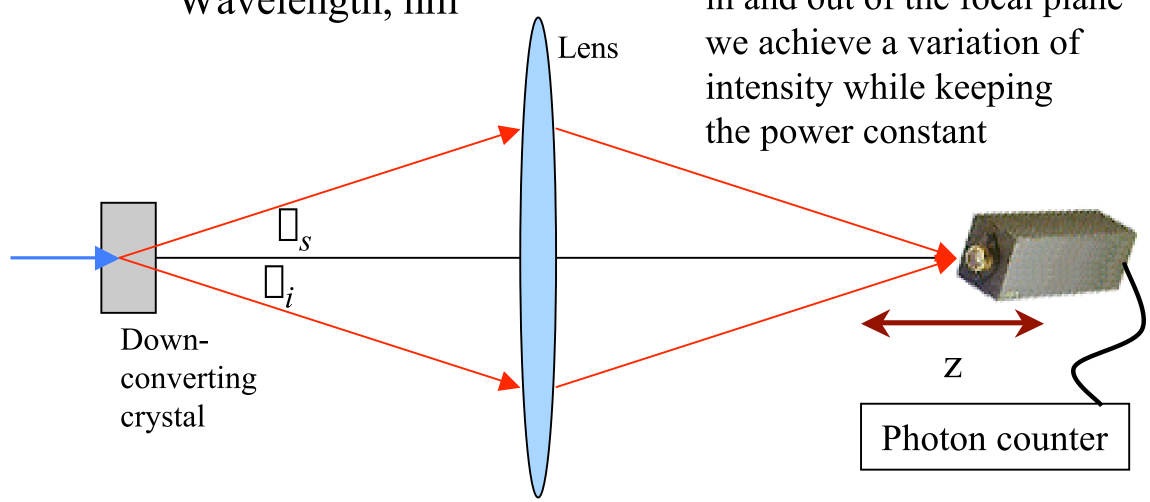
Motivation: to build a detector sensitive to photon pairs, but not to single photons.



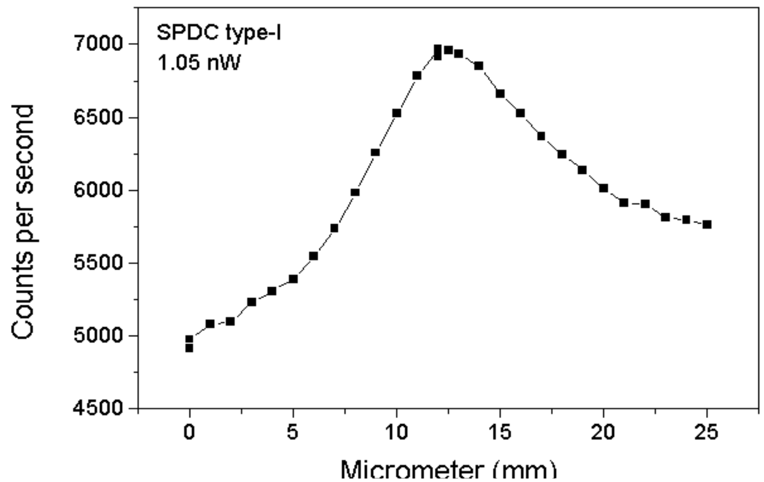
E.g.: [T. Hattori et al., Jpn. J. Appl. Phys. 39, 4793 (2000)] studied two-photon response of PMTs with 15 fs pulses.

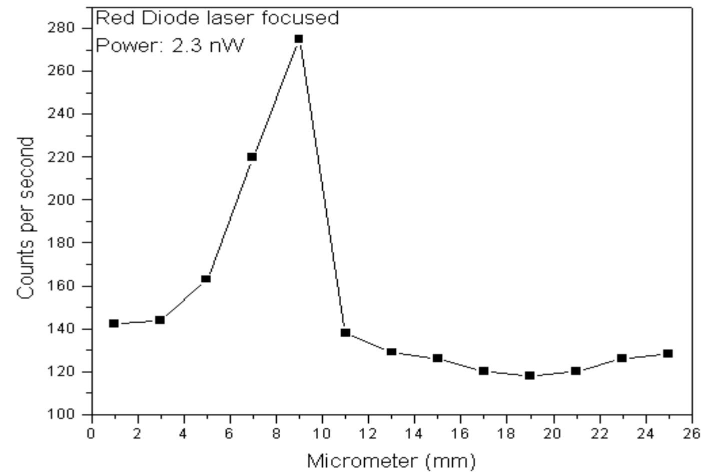


By moving the photocathode in and out of the focal plane we achieve a variation of intensity while keeping the power constant

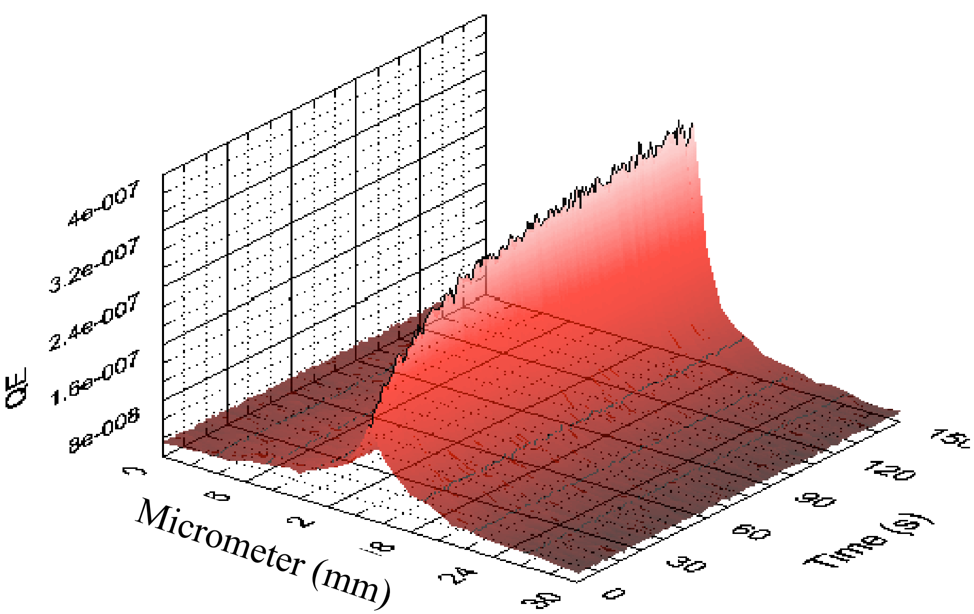


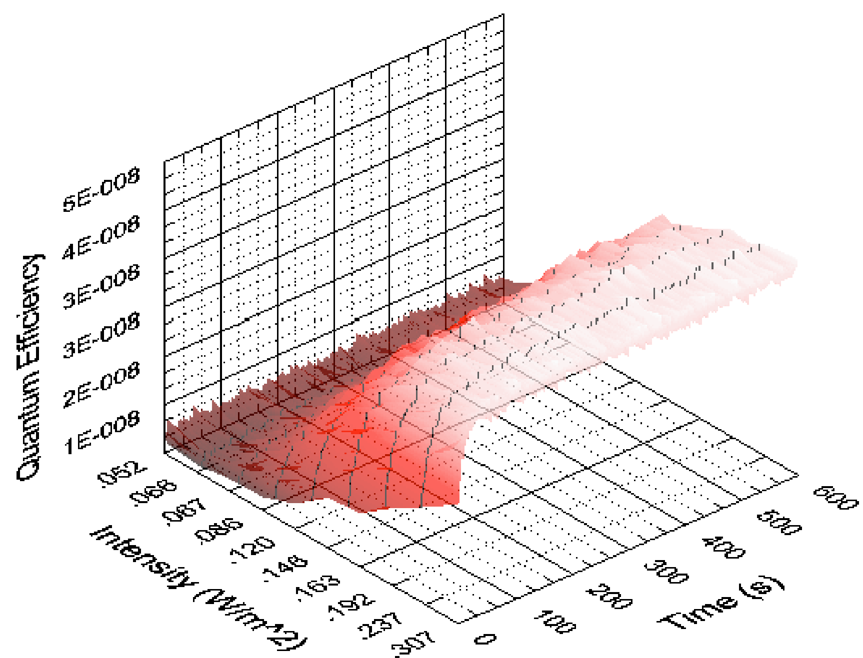
The results obtained with SPDC and with attenuated laser light (at 650 nm = 1.9 eV) look similar:





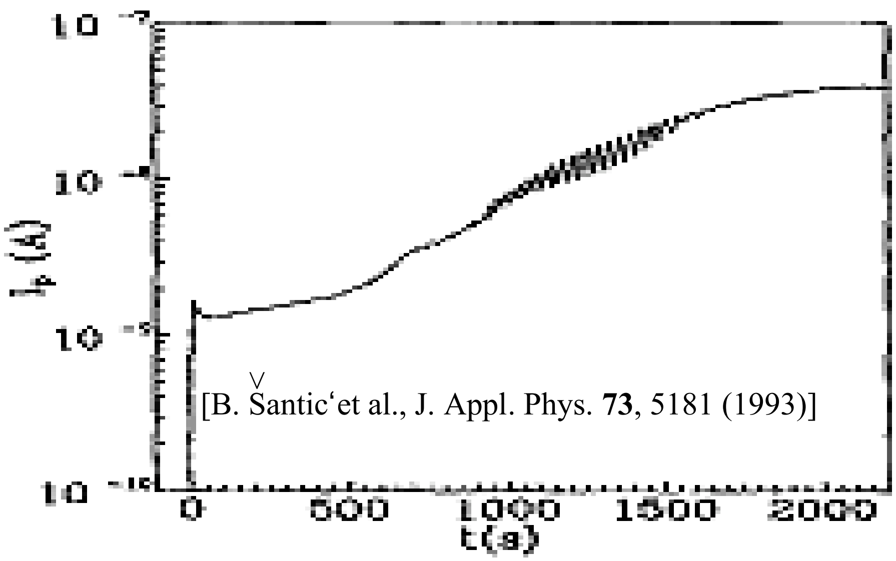
In addition to being nonlinear, the photocathode response is time-dependent:

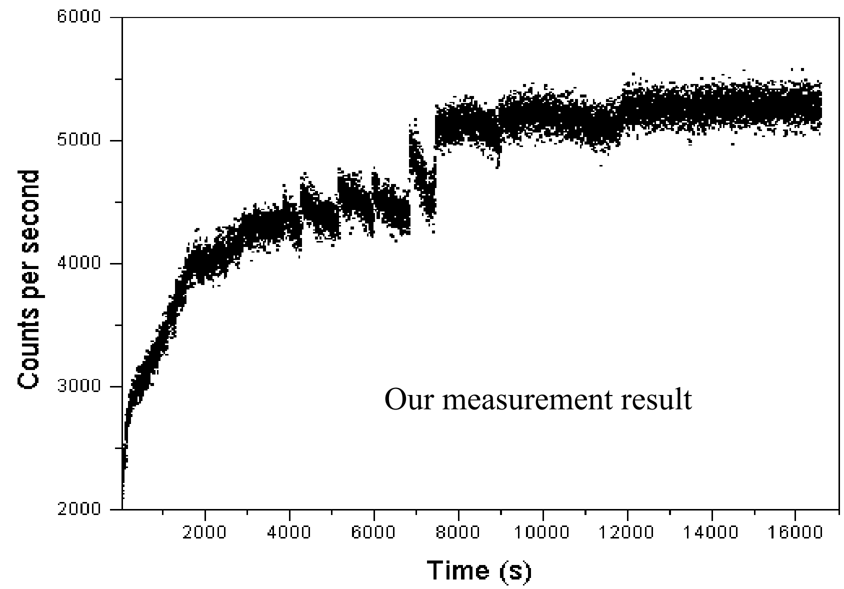




We therefore observe a photosensitization effect resembling the experimental observations by *[B. Šantić et al., J. Appl. Phys.* ***73****, 5181 (1993)]* for photoconductive current in GaAs at 70 K.

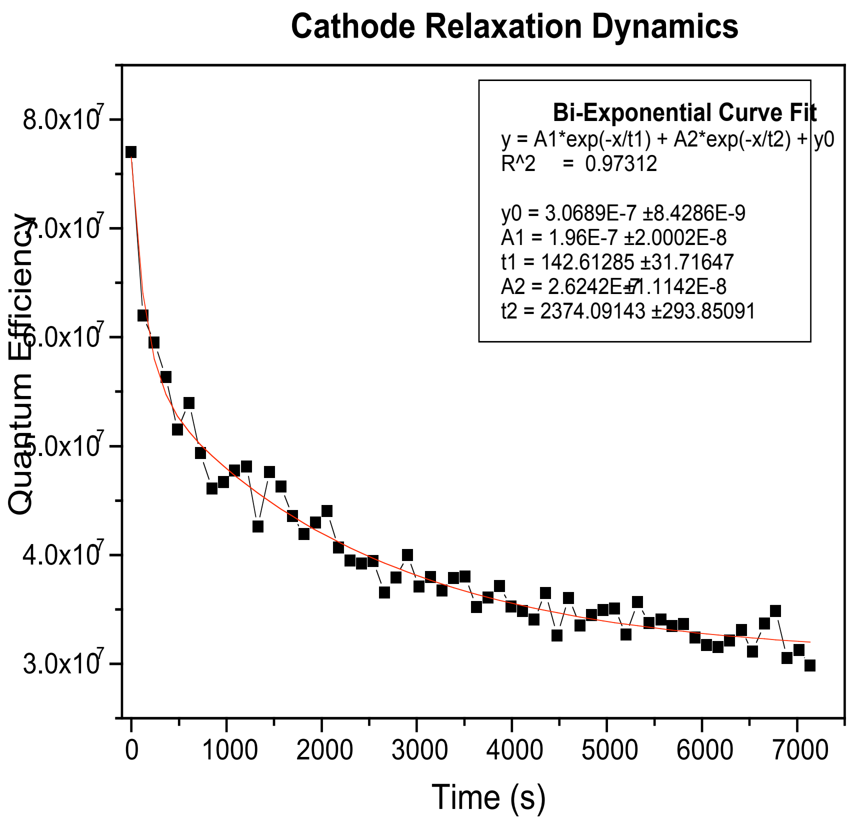
This effect may be explained as the filling of deep traps.

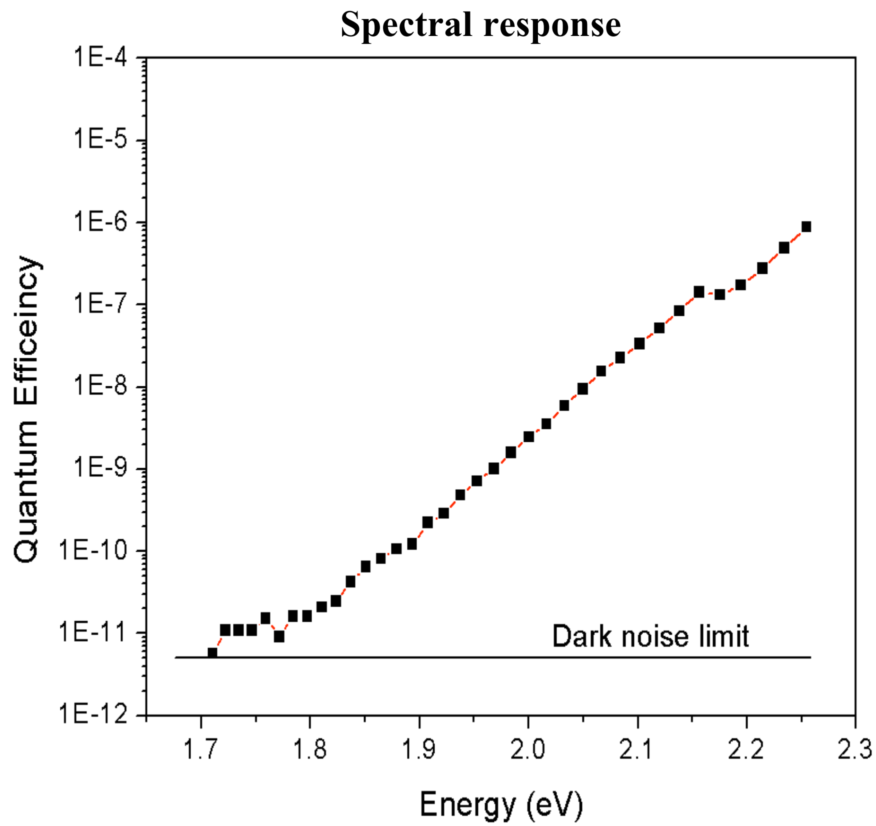




The “trapped” or intermediate states we observe have extremely long lifetime at room temperature! Studying their dynamical and spectral properties may be interesting for material characterization, and may suggest the way the Cs_2Te photocathode can be used for photon pair detection.

Relaxation dynamics and spectral two-photon sensitivity

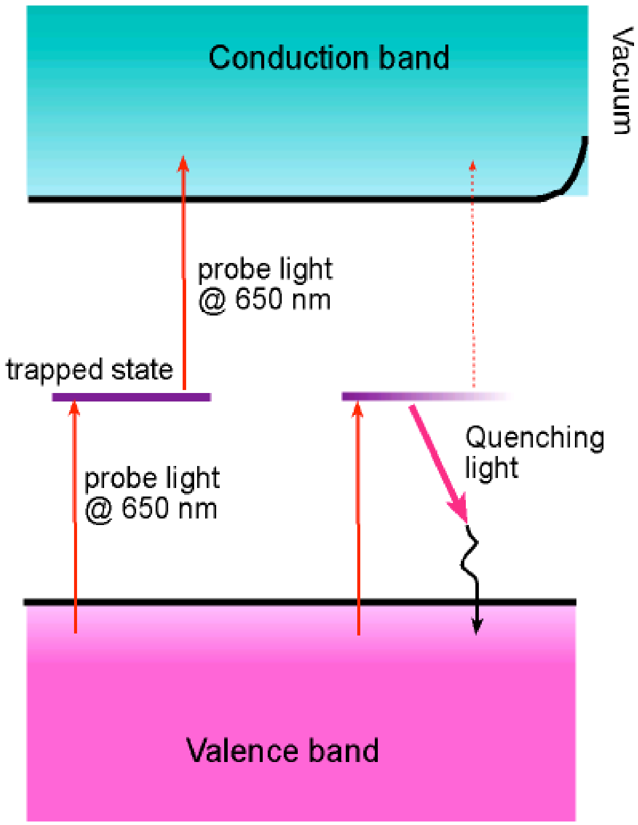


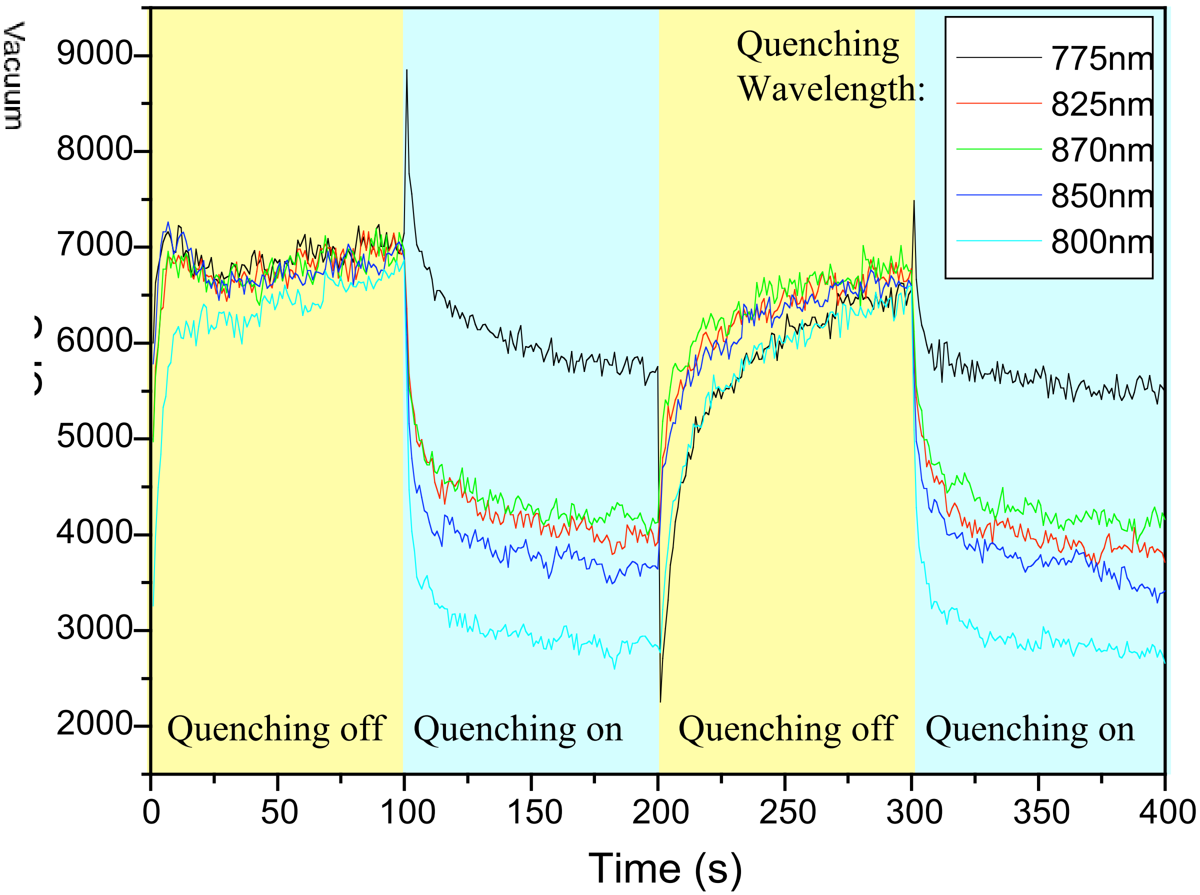


The normalized response (quantum efficiency) of a previously sensitized photocathode decay fits a bi-exponential law. This indicates the presence of at least two metastable levels inside the bandgap, with very long life time.

Quenching effect

The long-lived intermediate states can be de-populated by external radiation (the quenching effect)





This result suggests that a long-lived intermediate state is at least 1.6 eV (which corresponds to 775 nm) deep from the conduction band edge.

Summary and conclusions

We have formulated the phenomenological approach to two-photon detection based on various physical mechanisms. This approach allows one to directly use the results of two-photon experiments with classical sources for prediction of similar experiments outcome with quantum correlated sources, such as SPDC. Several such experiments have been discussed.